II.1 Development of a Low Cost 10 kW Tubular SOFC Power System

Objectives

- Design of a common low cost generator to meet all chosen markets.
- Development of an anode supported micro-tubular cell capable of twice the power density presently achieved.
- Design, build, and test an inverter with 94% efficiency for conversion of DC to AC electricity.
- Prototype testing of a natural gas fueled unit meeting and exceeding SECA Phase I goals.

Accomplishments

- **Successful Fabrication and Testing of a Closed End Isopressed Anode Tube:** Anode tubes, presently fabricated by extrusion, have been manufactured through isostatic pressing containing an integral closed end. Successful completion of this development allows the reduction in the number of steps required to make an anode tube from four to one significantly decreasing cost. This process also decreases the total manufacturing operation by removing the need for a metallic braze cap presently used to form a closed end.
- **Exceed 250 mW/cm^2 on Multiple Interconnection Cells:** A number of multiple interconnection cells have been manufactured achieving >250 mW/cm^2. This increases the average value from 120 mW/cm^2 thereby cutting the required number of cells in half for the same power level as well as cutting cost in half.
- **Demonstrate a Tubular SOFC Achieving >60 W/tube:** Further advancements in larger diameter tube technology and multiple take-off connections have been integrated into a single cell design. Previous advancements in isopressing technology have also been incorporated. These advancements take the single cell power from 5 W/tube at the start of the SECA program to >60 W/tube.
- **Cell Testing Exceeds 13,000 hours of Operation:** Cells that have been on test for 12,253 hours (59 thermal cycles) and 13,429 hours (70 thermal cycles) have been taken off test for analysis. These cells operated at or above 75% fuel utilization for the entirety of the test achieving high efficiency. The results of this post-test analysis will be used to enhance further generations of anode supported SOFCs.
- **Ceramic Interconnection Stack Test Exceeds 2,400 hours of Operation:** The first small stack test incorporating ceramic interconnections has exceeded 2,400 hours of operation and completed thirteen thermal cycles. To date, there has been no noticeable power degradation.
- **Prototype Assembly:** A prototype system has been partially fabricated to complete SECA Phase I testing. This system incorporates the latest cell technology advancements as well as generator and balance of plant (BOP) enhancements. The unit will be tested in the next few months according to the outlined SECA test plan.

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Introduction

The Acumentrics SECA project has focused on the design and manufacture of micro-tubular SOFC power systems approaching twice the power density now achieved from state-of-the-art anode supported tubular designs. Based upon DOE funding and a focused research effort, these cells are now very near to achieving this goal. These units will be capable of entry into the telecommunication, remote residential, and military markets. Operation on fuels including natural gas and propane will be developed for the telecommunication and remote residential markets. Operation on liquid fuels, including diesel and JP-8, will be developed for the military markets.

Working with Acumentrics to define market segments and market requirements are a number of key investors that are strategic players in their respective markets. They include:

- Chevron Texaco for remote markets and liquid fuels.
- General Dynamics for liquid fuels as well as military operations.
- Northeast Utilities and NiSource for integration in the natural gas and electricity infrastructure.
- Sumitomo Corporation of Japan for introduction and product definition into the Japanese market.

Approach

To achieve the final SECA goal of a manufactured unit cost of less than $400/kW, work can focus on increasing cell power thereby decreasing the number of cells per kilowatt or decreasing the cost of each component. With such an aggressive goal, work must focus on both paths. To increase cell power, work is centered on improved materials as well as enhancements in geometry. Cells with increased anode conductivities to decrease electrical bus losses are being investigated. Improved conductivity of cathodes is also being investigated to decrease the potential loss associated with the electrochemical reaction on the air side. Increases in cell tube diameter as well as multiple contact points along the length are also being studied.

For subsystem cost reductions, the machine is divided into four major sub-systems: the SOFC generator, the control system, the power conditioning system, and the fuel and airflow system. In the SOFC generator, advanced materials and manufacturing techniques are being investigated including metal injection molding (MIM) as well as metal stampings. Vacuum cast insulation to near net shape is also being considered. For the control system, a controller area network bus (CANBUS) architecture is being developed as well as integration of control of all valves and power electronics. For the power electronics sub-system, the focus is on improving the overall DC/AC conversion efficiency to avoid excessive losses which compromise overall system efficiency and require more cells and therefore more cost. In the air and fuel sub-system, removal of redundant components as well as qualification of equivalent components at lower cost is the path chosen.

Results

Single Cell Power

In the past fiscal year, substantial advancements have been made in increasing individual cell power. To achieve the Phase III SECA goal of <$400/kW, continual strides must be made in cell power to reduce the number of cells as well as overall size of the machine. By decreasing size and weight, there is a direct relationship with overall cost at high volumes. Figure 1 shows the progress in increasing the power/tube from the Acumentrics anode supported cell. The lower curves, achieved in the 2002 to 2003 timeframe, show a cell with a peak power of 7-15 W/tube. In the late 2005 timeframe, power was enhanced to >60 W/tube representing a 4-8x increase in power from a single tube. What is also worth noting is that the same number of manufacturing steps is required for the 7 W tube as those needed for a 60 W tube.

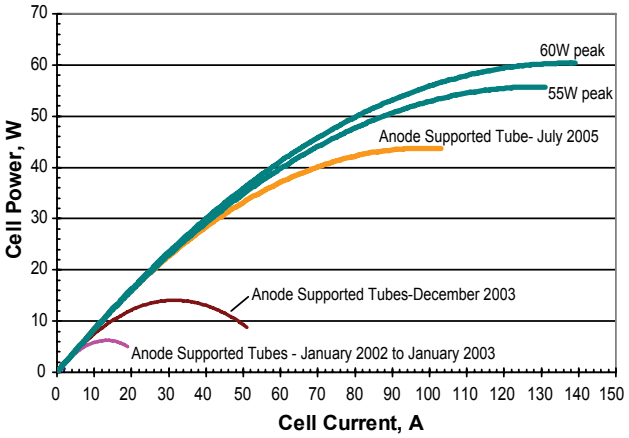

FIGURE 1. Single Cell Power Evolution

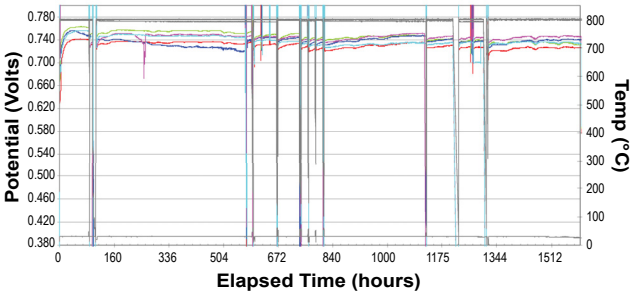

FIGURE 2. Single Cell Performance Stability

Performance stability of these latest high power cells has also been improved from those of the 2002 pre-SECA stage. Figure 2 shows a voltage versus time plot for a group of five cells from the latest generation of multiple interconnection cells. The plot shows that for operating times exceeding 1,500 hours, the degradation of these cells is well below the SECA Phase I and II goals of <2% and <1%/500 hours and approaching that of <0.1%/500 hours for Phase III. What should be noted is that these operating times are nearing the requirements for stand-by or peaking generators which would be needed for 100 kW+ machines to offset high demand loads. Cells of this vintage have now been tested for >4,000 hours with very stable performance and will continue to validate the requirements of 40,000 hours for continuous duty machines.

Stack Performance

In addition to substantial strides in cell performance, significant progress has been made in stack performance. To complete the SECA Phase I machine testing, the unit must complete >1,500 hours of operation with >80% availability, >35% efficiency, and <4%/1,000 hours degradation. To validate the

Acumentrics design, a 24-cell stack was tested under the Phase I test conditions to assure that these conditions could be met. Figure 3 shows the performance timeline for this stack for a greater than 2,000-hour run. As can be seen in the figure, the unit ran for greater than 1,900 hours and achieved an availability of >88%. A peak efficiency of 35.2% was achieved and a degradation of 1.2%/1,000 hours was achieved. Based upon these results, Acumentrics is confident in their ability to pass the SECA Phase I performance goals.

Generator Design

Work has continued in cost reduction of the generator design with the goal of a simple system to site and operate requiring a minimal amount of site services. Figure 4 shows the existing system capable of achieving >5 kW electrical output. This system is mounted in a NEMA 3R cabinet for outdoor installation with two separate cabinet spaces: one for the fuel cell generator and gaseous balance of plant components and the other for the electrical and control devices. Progress has been made in advancing both metallic and ceramic recuperators for thermal recovery on the SOFC stack side as well as cost and power reduction on the valve and blower components. All of these improvements reduce the parasitic load thereby increasing the overall net electrical output. On the electrical side, the integration of a >98% efficient DC/DC converter as well as a >94% DC/AC inverter has been progressing. This unit will be packaged and integrated into the existing machine in the next fiscal year.

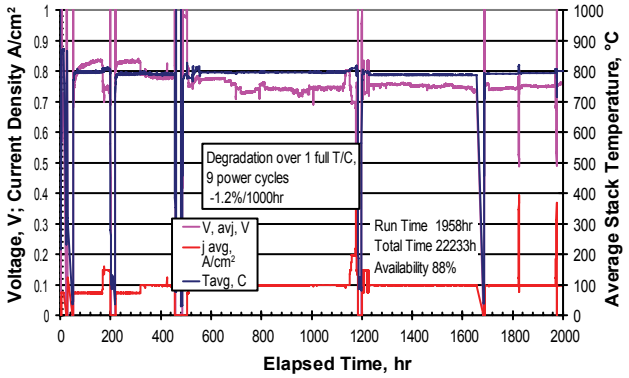

FIGURE 3. SOFC Stack Performance Stability

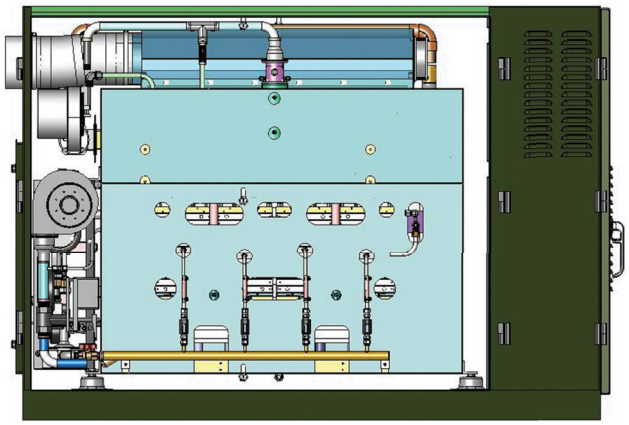

FIGURE 4. Generator Configuration

Conclusions and Future Directions

Continual advancements have been made toward the SECA cost and performance targets in the Acumentrics' SOFC project. These advancements can be summed as:

- Cell power densities exceeding 250 mW/cm^2 or 2x greater than previous technology.
- Individual cell power exceeding 60 W/tube or 4-8x previous limits.
- Stack stabilities with slightly over 1%/1,000 hour degradation or only 30% of the SECA allowable target.
- Generator design with significant size and weight reductions over pre-SECA designs well suited for mass production.

The following activities are planned to futher advance progress toward the SECA targets:

- **Complete SECA Phase I Generator Performance Testing:** The SECA Phase I generator is nearing completion of manufacture. The test plan is near final review between Acumentrics and the DOE project manager. The unit will then be tested according to this plan.
- **Complete 95% Efficient Inverter Development:** By demonstrating the integration of an inverter capable of over 95% efficiency versus the market standard of 82-90%, overall system efficiencies can rise by nearly 5 percentage points. This improvement in overall efficiency can be taken as fuel savings to reduce the overall cost of electricity (COE). Another option is to operate the fuel cell stack at a lower cell voltage point thereby increasing the individual cell power requiring fewer fuel cells and less overall capital cost.
- **Complete Preliminary Testing on Liquid Fuels and Integration with an SOFC Stack:** Preliminary tests on liquid fuel delivery to single SOFC tubes has been completed in the past with good success. To further evolve to a complete machine, existing reformer technology for liquid fuels will be integrated with an SOFC stack to determine issues such as thermal balance, flow distribution,

and potential carbon formation. These results will be used to successfully design a complete system capable of operation on commercially available liquid fuels.

FY 2006 Publications/Presentations

1. "Status of the Acumentrics SOFC Program", N.F. Bessette, Presented at the 2005 Fuel Cell Seminar, Palm Springs, CA, November 16, 2005.